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Research Article

Tidal Current Influence on Distributing Submarine Groundwater Discharge (SGD) Area in the North Lombok Waters, Indonesia

Pengaruh Arus Pasang Surut dalam Distribusi Keluaran Air Tanah Lepas Pantai (KALP) di Perairan Lombok Utara, Indonesia

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Abstract

Submarine Groundwater Discharge (SGD) has been found in the North Lombok Island. This phenomenon is strongly related to the watershed from Rinjani Mountain permeated in the form of underwater seepages. The largest seepage was observed in Krakas Beach. The emergence of these seepages may affect water quality and nutrient pollution in the surrounding by which the distribution is mainly induced by the tidal current regime. This study aimed to determine the influence of tidal current on low-temperature groundwater distribution and to analyze the environmental issues resulted from this phenomenon. Flow model and statistical analysis were employed to determine the transport pattern of SGD. The tidal current moved southwestward during the high tidal condition ranging from 0-0.15 cm/s. While tidal current flowed northeastward during the low tidal condition ranging from 0-0.3 cm/s. The temperature fluctuation follows the changes of surface elevation around SGD in which the correlation value between those two parameters reached 63 percent. This proves that the cold-water transportation depends on the fluctuation of tidal current (tidal pumping), resulting in the imbalanced ecosystem, especially during the high tidal condition when a greater water mass transport takes place.

Abstrak

Keluaran Air Tanah Lepas Pantai (KALP) telah ditemukan di utara Pulau Lombok. Fenomena ini sangat dipengaruhi oleh daerah aliran air Gunung Rinjani yang meresap dalam bentuk rembesan bawah air. Rembesan terbesar diketahui berada di Pantai Krakas. Kemunculan rembesan ini mungkin berdampak pada kualitas perairan dan polusi nutrien di sekitarnya yang mana distribusinya sangat dipicu oleh pengaruh arus pasang surut. Tujuan dari penelitian ini adalah untuk mengetahui pengaruh dari arus pasang surut terhadap distribusi air dingin dan menganalisis masalah lingkungan akibat dari kondisi tersebut. Arus pasang surut bergerak menuju barat daya saat kondisi pasang berkisar antara 0-0,15 cm/s, sedangkan arus pasang surut bergerak menuju timur laut pada kondisi surut berkisar antara 0-0,32 cm/s. Fluktuasi suhu mengikuti perubahan elevasi muka air di lokasi KALP dimana nilai korelasi dari kedua parameter tersebut mencapai 63 persen. Hal ini membuktikan bahwa transpor air dingin bergantung pada fluktuasi arus pasang surut, menyebabkan ketidakseimbangan ekosistem, khususnya pada kondisi pasang ketika mekanisme transpor masa air yang lebih besar sedang berlangsung.

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1. Introduction

Submarine Groundwater Discharge (SGD) is a seepage phenomenon that emerges near the coast (near-shore seepage), seepage in the seabed, and spring discharge (Lubis *et al*., 2011). SGD is triggered by the difference of hydraulic gradient of surface groundwater due to its degraded concentrations. Regionally, the emergence of groundwater discharge is induced by several parameters such as climate, geological condition, topography, land, and rock type, rock permeability, the gradient of surface water pressure and tides in the intertidal area (Thompson *et al*., 2007). This resource is imperative to occupy the freshwater needs in the coastal area. One of the potential SGD outfalls is located in the north Lombok that spreads out along the coast with huge discharges of groundwater.

Due to the steep slope around Rinjani Mountain, the cold water has flowed from the higher place to the coast through seepages. SGD in the North Lombok has identified in northern and eastern areas (Bakti *et al*., 2012). There are several seepages which the biggest one is located around 100-250 m from Krakas Beach. This SGD has been utilized by the local people in which it is connected via a long pipe, so locals could consume the freshwater effortlessly (Figure 1). Unfortunately, that pipe was no-longer-used nowadays. Several smaller SGD sources were also identified in the surrounding among coral reefs (Lestiana *et al*., 2017), resulted in an imbalanced ecosystem. This is proved by the unlivable biota around SGD sources (Figure 1).

The SGD brings low temperatures that may also contain a high concentration of nutrients and minerals. This condition strongly affects the environmental condition in the surrounding area where corals and the other biota could not live (Figure 1). The cold water is mainly distributed by winds, tides, and currents. Tidal current plays a role in this regime where the fluctuation of water temperature is possibly influenced by the changes in surface elevation (tidal pumping) (Boehm *et al*., 2002). The SGD area is positioned in the intertidal area that rapid longshore current flow and higher transport mechanisms take place (Johan *et al*., 2018).

Studies about SGD have been developed since the last 2000 in the form of journals and maps. Meanwhile, SGD in Indonesia was not explored yet indeed many SGDs potentially could be explored in term of studying groundwater utilization. Some previous studies related to SGD in Lombok waters are published by Bakti *et al*., (2010), Bakti *et al*., (2012), and Lubis *et al*., (2011) that focused on defining the SGD geologically and the locations of SGD. While, identifying the role of tidal current in distributing cold water is essential, as our known that sea current has a strong role in the coastal area in term of water mass movements. Moreover, Lombok Strait is one of the Indonesian Throughflow gates that strongly related to the transport mechanism in the surrounding. Thus, this study aims to determine the influence of tidal current on distributing the cold freshwater and analyze the environmental issue due to SGD.

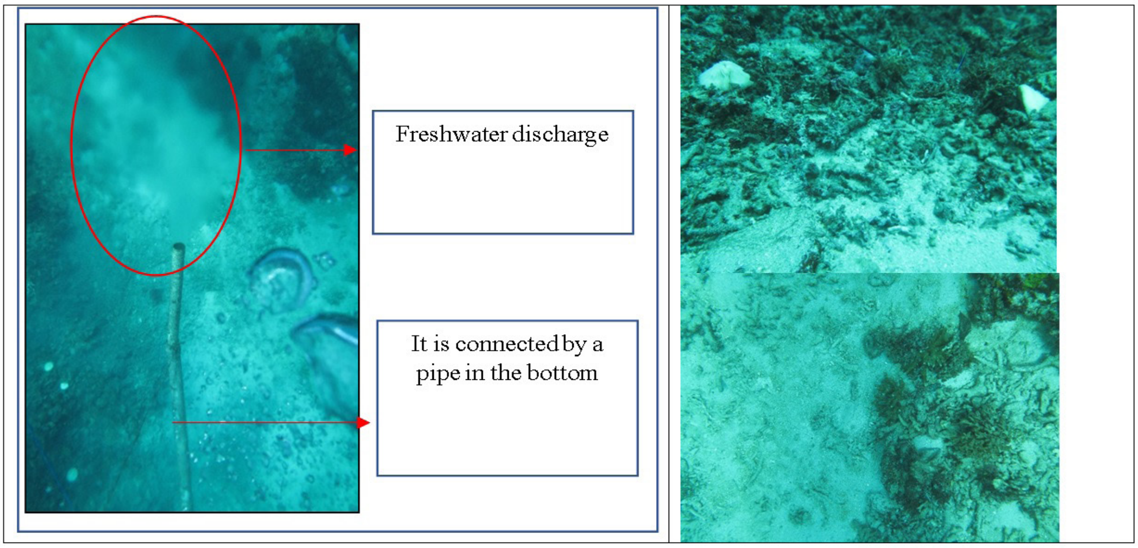


Figure 1. Outfall condition of SGD (left) and its surrounding environment (right) in the Krakas Village

2. Materials and Methods

2.1 Survey Time and Study Location

This study was conducted on March 26-29th, 2016 in Krakas Village coast, North Lombok Sub-District. The location was directly bordered by Lombok Strait which is one of ITF (Indonesian Through Flow) gates, resulting in the climatic factors influences in water. The existence of Rinjani mountain triggers low-temperature groundwater to be absorbed and flowed

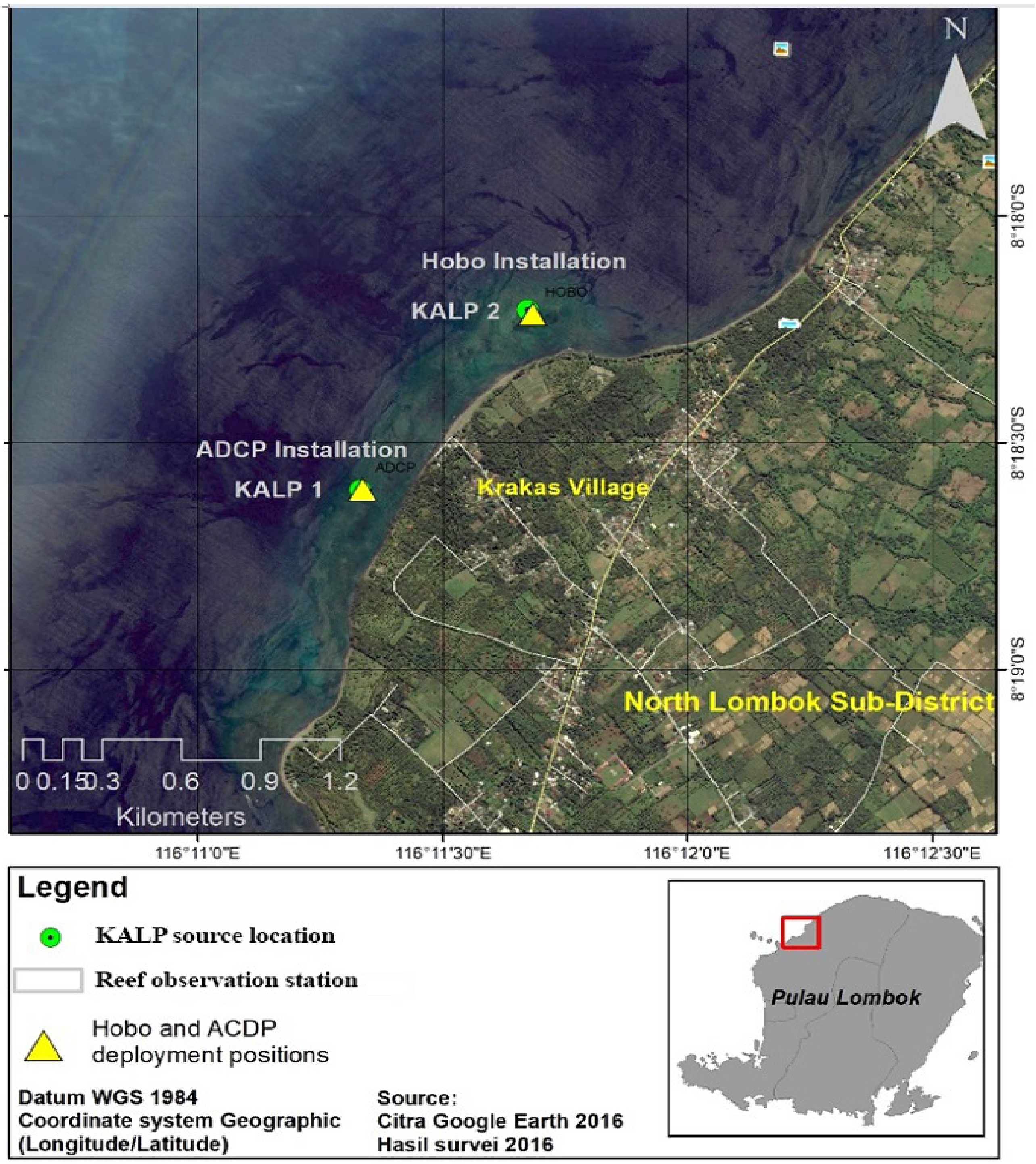


Figure 2. Study location map

through underwater seepages. It emerges in the low-pressure area such as the beach and nearshore. Many SGD sources have been identified in Krakas Beach (Bakti *et al*., 2012). In this study, we decided to observe the two biggest SGD sources (Figure 2).

2.2 Study Materials

The primary data consist of tides, temperature, and currents measured directly in the field. Tide and temperature data were obtained using HOBO-ware mounted during a month in the SGD sources. While horizontal temperature data were obtained using TOA DKK water quality checker measured in the field. ADCP-Nortek (Acoustic Doppler Current Profiler) was deployed for two days of measurement. Therefore, the secondary data consist of bathymetry and coastline digitation. Bathymetry data were retrieved from the GEBCO (General Bathymetry Chart of The Ocean) web page (https://www.gebco.net/data_and_products/gridded_bathymetry_data/).

2.3 Hydrodynamic Analysis

Water circulation around SGD sources was simulated using the hydrodynamic model which illustrates the distribution pattern of sea surface temperature modeled for 15 days representing the neap and spring tidal conditions. Results will be depicted in the form of two-dimensional for four tidal extreme conditions (Warren and Bach, 1992; Mehdiabadi *et al*., 2015).

Bathymetry data and coastline digitation were used as the model input. Surface elevation data were obtained by executing NAO tide software in which the time series data resulted would be analyzed. The hydrodynamic model set-up is shown in Table 1.Wind data are considered to simulate the flow model because the study area is categorized into the wind-driven area and located nearshore (shallow water) where the wind influence took place in generating longshore current.

Table 1. Set-up for hydrodynamic model

Parameter	Implemented in simulation
Simulation time	Number of time step = 350 Time step interval = 600 second Start and stop simulation date = 5/03/2016 24.00 – 5/05/2016 00.50
Mesh boundary	Bathymetry = GEBCO bathymetry data Coastline = Google Earth Image digitation
Wind Forcing	Include-varying in time, constant in domain
Flood and Dry	Drying depth = 0.005 m Flooding depth = 0.05 m Wetting depth = 0.1 m
Boundary condition	Tide forecasting with coordinates: 1. Longitude: 115.98290 E; Latitude: -8.3783 S 2. Longitude: 115.96072 E; Latitude: -8.2476 S 3. Longitude: 116.12450 E; Latitude: -8.0931 S 4. Longitude: 116.30377 E; Latitude: -8.1191 S

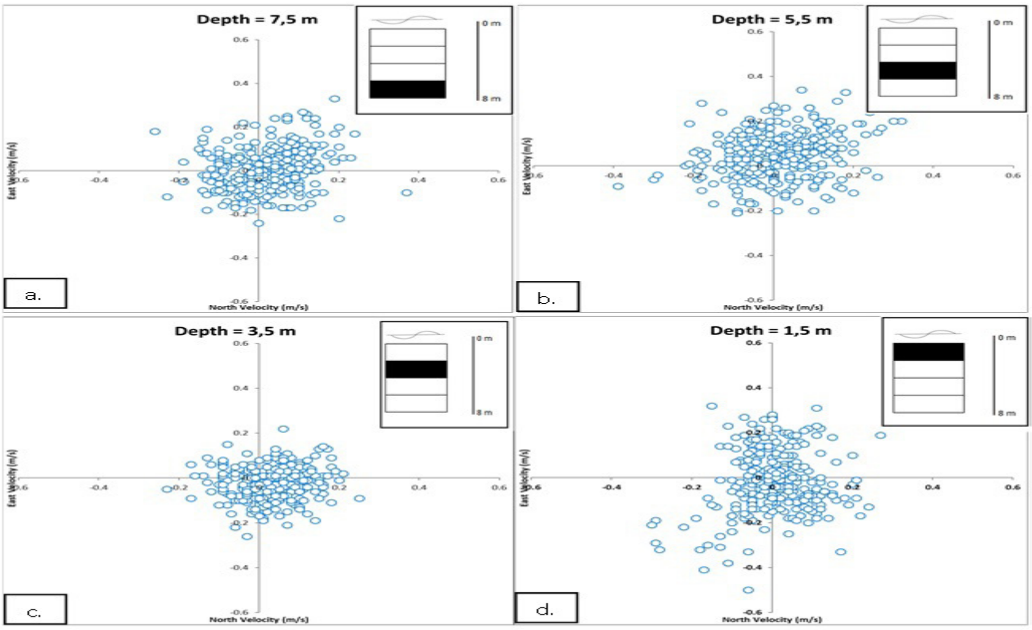


Figure 3. Scatterplot of sea current in the SGD source; a. the current profile in the depth of 1.5 meters from the surface; b. the current profile in the depth of 3.5 meters from the surface; c. the current profile in the depth of 5.5 meters from the surface; d. the current profile in depth of 7.5 meters from the surface.

Currents and tides data were also applied to validate the flow model results by which we employ RMSE (Root Mean Square Error) formula (Wisha *et al.*, 2018) as follow:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2} \quad (1)$$

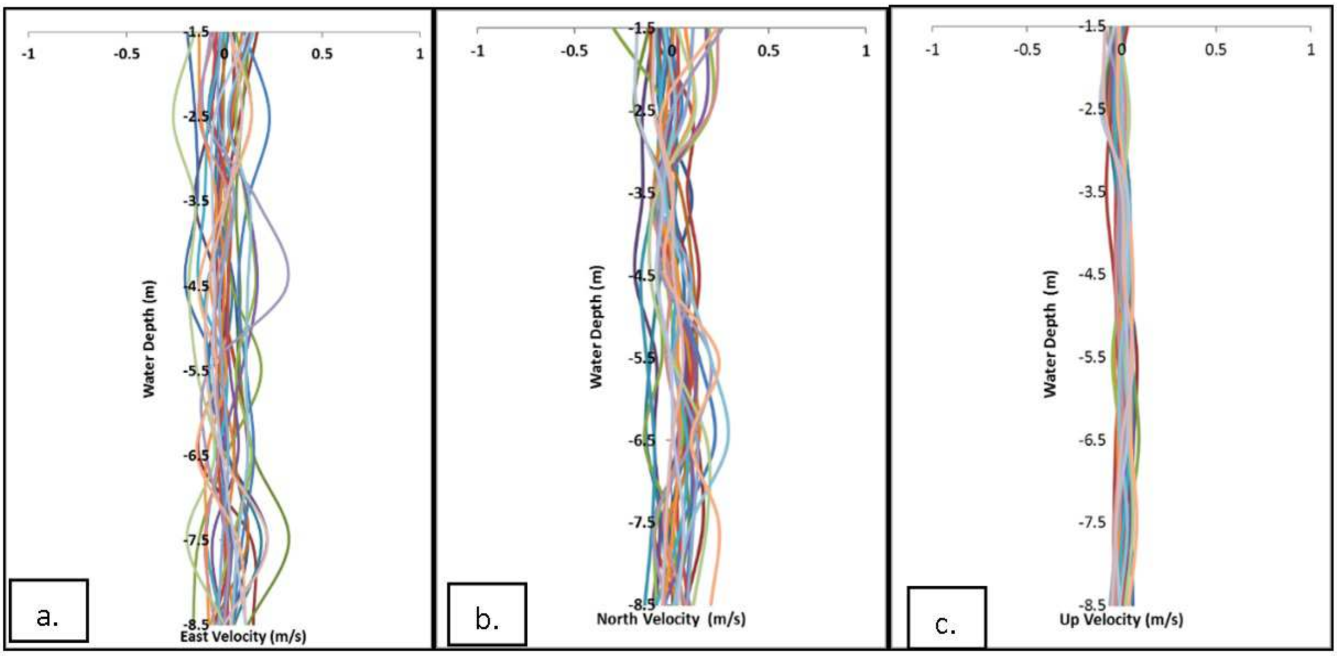
where:
N = Total data used
x_i = Model data result
y_i = Field measurement data result

3. Results and Discussion

3.1 Sea Currents Profile in the SGD Area

Current velocity scatterplots (Figure 3) show that the current direction rotated counter-clockwise which illustrates the regime of spiral Ekman related to vertical water-mass movements in the southern hemisphere. These scatterplots also depict that the sea current profile was not only evoked by tides, also winds and waves. It is proved by the elliptical tidal current with an erratic and relatively rounded form. This bias is strongly induced by the wind-driven current on the surface. That is why the arbitrary scatter plot profile is identified on the surface where the wind's energy transfer is maximal. Indeed, the influence of wind is still observed in the bottom due to the shallow area of study. From this analysis, we found that In the North Lombok Waters, sea current profile is strongly evoked by tides-winds regimes that might be related to Indonesian Throughflow in Lombok Strait as one of its gates. Sea current relatively moved toward the northeast and north with a stable speed in the layer of 7.5 m and 5.5 m which the current speed ranged from -0.33 – 0.38 m/s and -0.4 – 0.36 m/s respectively. In the 3.5-1.5 m depth, the current direction predominantly moved northeastward and southwestward which the current speed ranged from -0.22 – 0.23 m/s and – 0.3 – 0.28 m/s respectively. According to speed vertical changes, there was an anomaly whereby the groundwater discharge velocity takes place in evoking higher current speed at the bottom near the source. This was possible because we deployed the ADCP right on the SGD source. Moreover, a scatterplot was created by comparing the two current velocity data that were north (u) and east (v) velocity contained the negative and positive value of speed showing the particle movement with changes of direction. The domination of positive value in the scatterplots depicts most particles move surface-ward. This might be caused by the discharge of groundwater that flows vertically toward the surface.

Figure 4 illustrates the vertical current movements are quite erratic. The east and north velocity vertical profiles (Figure 4a and 4b) show that the sea current move surface-ward arbitrarily, the current speed was higher in the bottom which declines in the water column and becomes faster on the surface. This agreement proves that the sea current vertical profile anomaly takes place possibly related to the regime of SGD streamflow. The up-velocity profile seems like generally stable from the bottom to the surface.



Figures 4. Vertical profile of sea current in the SGD spot; a. vertical profile for east velocity; b. vertical profile for north velocity; c. vertical profile for up velocity.

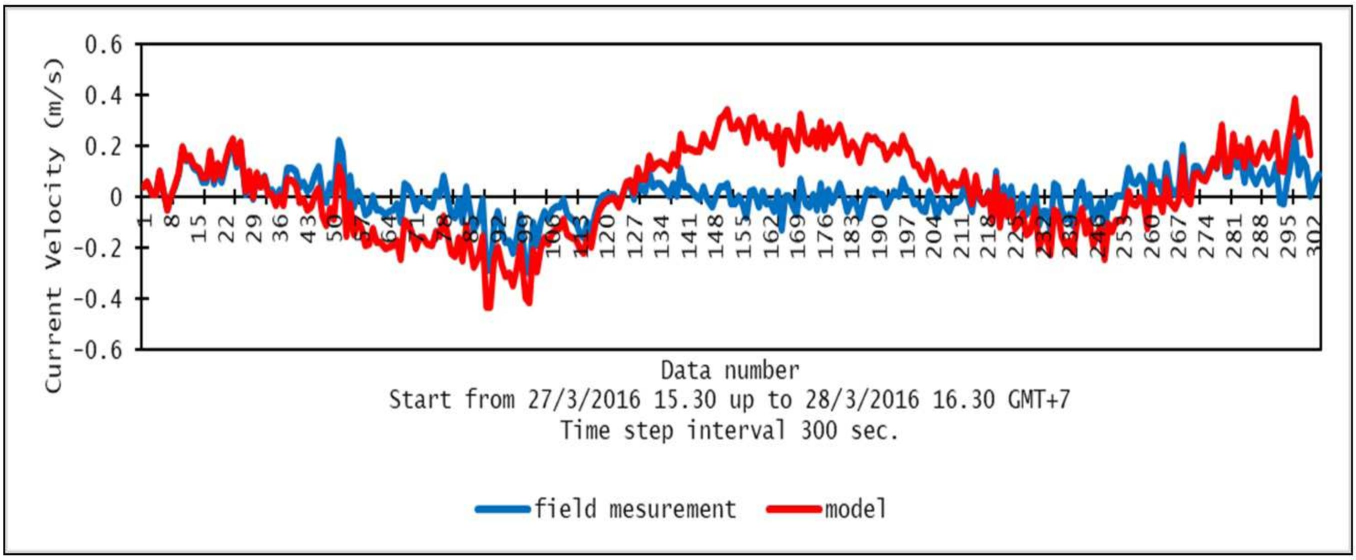


Figure 5. Zonal component of currents (u) data validation

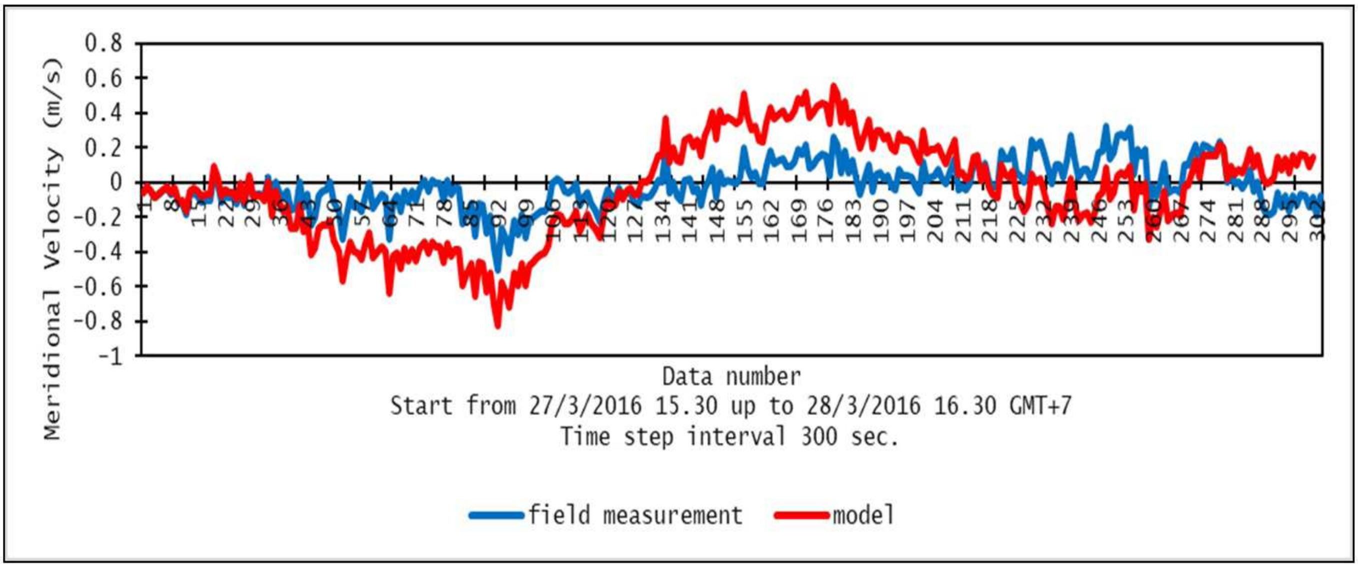


Figure 6. Meridional component of currents (v) data validation

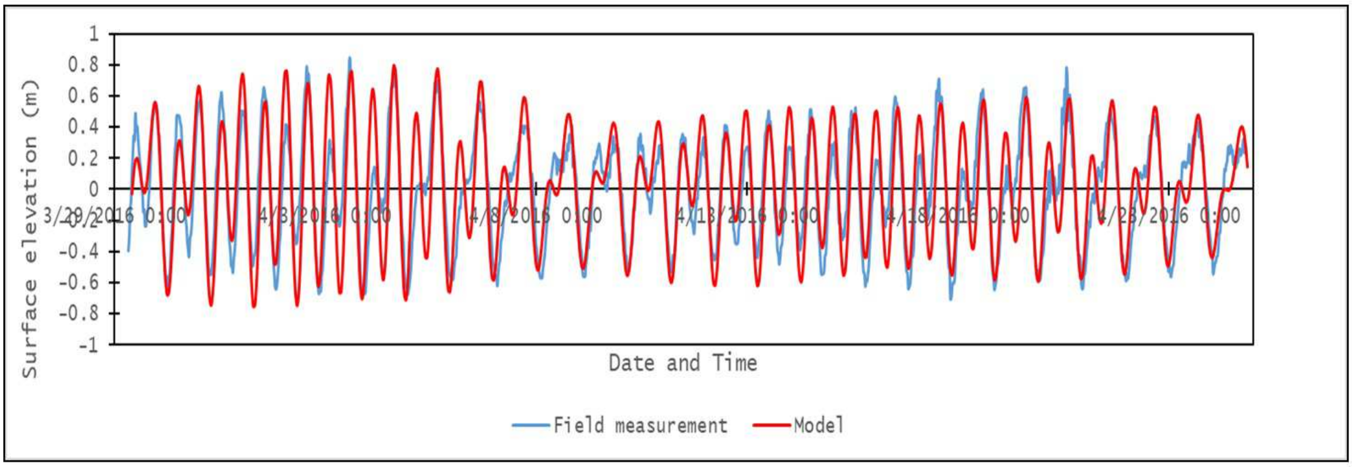


Figure 7. Surface elevation data validation

The declination of current velocity in the water column might be related to density changes in which the groundwater density is lower than seawater, this degradation strongly influences the vertical transport of water masses. The emergence of SGD underwater flows the groundwater with a low temperature by which the density and salinity were lower than seawater (Surić *et al*., 2015). This difference in density and salinity was shown in the blurred area that it is like oil in the water (Figure 1).

3.2 Hydrodynamic Model Validation

The model validation was created by comparing the model result and field measurement data (Bayhaqi *et al*., 2018; Lazure *et al*., 2009; Wisha *et al*., 2016) in which parameters validated are surface elevation, zonal (u) and meridional (v) component of currents. From those comparisons, we obtained RMSE values that represent the bias data resulted from the model simulation. For the examination of the zonal and meridional component of currents, the error value reached 11.32 % and 12.46 % respectively.

Velocity component data examined were only for two days of simulation, because it was adjusted to field measurement (ADCP) for only three days. Those comparisons show the similar phases between model and field data by which the zonal component velocity ranged from -0.4 up to 0.38 m/s (Figure 5). We found anomalies of model data that seem more erratic which fluctuate higher during the high tidal condition and reach the lowest of negative speed during the low tidal condition even though the phases still have the same patterns. This also applies to the meridional component of the current by which the deviation was slightly smaller. The velocity ranged from -0.8 up to 0.6 m/s and -0.42 up to 0.28 m/s for model result and field measurement data respectively. The lower negative velocity indicates that water mass transport tends to be settled and flowed in the surface bottom (Liang *et al*., 2003). This may trigger the SGD to pollute the surrounding environment near the bottom. This was also proved by the unlivable biota in the surrounding of sources (Figure 6).

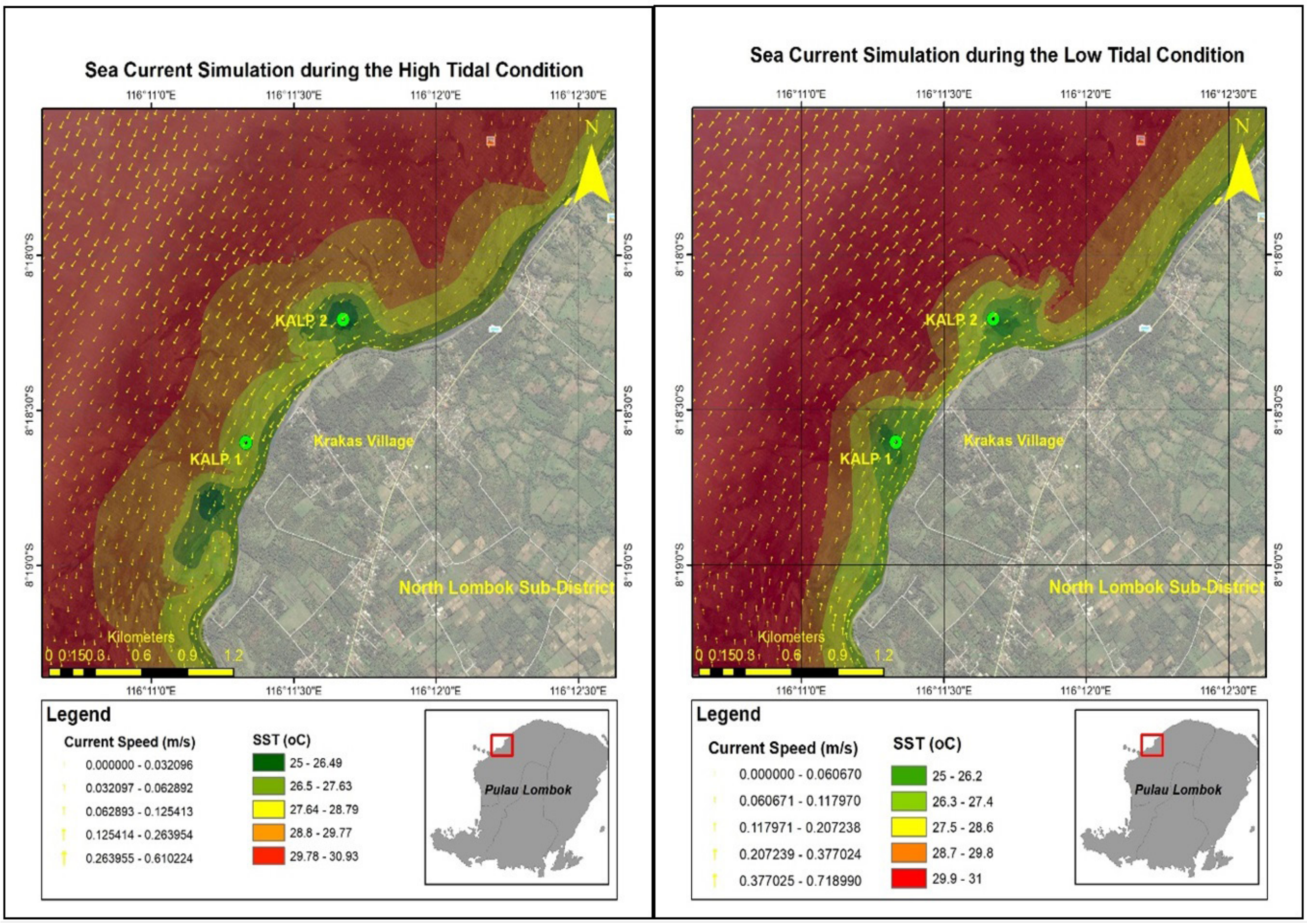


Figure 8. Spatial distribution of surface temperature driven by currents during flood tides (left) and ebb tides (right)

The examination was applied to surface elevation data as well which the RMSE obtained of 8.79%. Based on measurement, the tidal type of North Lombok waters was mixed tide prevailing semidiurnal where the elevation changes twice during 12 hours, this was also mentioned by Pratomo *et al*., (2017) and Junaidi *et al*., (2018). A similar tidal phase was also identified that shows the good execution of the model developed (Figure 7). The tidal range reached 1.8 meters during spring tides and a meter during neap tides. There were some anomalies in Figure 7 which the elevation was not uniform at the neap tidal conditions. Several bias factors are identified triggering the arbitrary formation of tidal fluctuation. This probably indicates that the wind-waves influence takes place. During the neap tidal conditions, the astronomical forces become weaker, resulting in dominated higher external forces. The wind-wave influence was intensely occurred due to the shallower area during the neap conditions, this also increases the chance of wind-driven current influence. The formation period of wind-wave was in conjunction with the changes of tides, this was why waves and tides were influencing each other. Thus, the surface fluctuation is more spasmodic.

3.3 The spatial influence of Sea-current on temperature distributions

At the displacement time toward high tidal conditions, the water motion was relatively faster than other sea-level positions. Current speed ranged from 0 up to 0.61 m/s. The direction predominantly moved westward and southwestward. While at the displacement time toward low tidal conditions, the current speed ranged from 0 up to 0.71 m/s which the direction predominantly moved eastward and northeastward (Figure 8). According to previous studies, Rachmayani *et al*., (2006) defined the tidal current magnitude in the North Lombok ranged from 0 up to 0.5 cm/s during flood tide, furthermore Ningsih *et al*., (2018) reported that the tidal in the north Lombok Strait was a semi-diurnal cycle and the tidal current amplitude ranged from 20-50 cm/s. The replacement phase of tidal elevation was followed by the tidal energy release which affects the current speed elevation during the low tidal condition (Wisha *et al*., 2017). The shallow water in the study area also has a significant role in generating sea current characteristics that control the horizontal distribution of SGD along the coastline (Figure 8). Low-temperature groundwater (26-28.79°C) released through seepages was propagated by sea currents in which the direction was in line with the sea current dominant direction. The SGD flows northeastward during the low tidal condition and southwestward during the high tidal condition, respectively. The horizontal distribution of SGD frequently occurs when the flood tides take place, while during ebb tides the distribution was strongly influenced by the rip and longshore currents in which the propagation of SGD with low temperature was just spinning around the source.

The distribution of temperature in the surrounding may trigger the environmental imbalance due to the extreme changes in temperature. This condition has a role in controlling the biogeochemical process and the water quality as well. A previous study (Bakti *et al*., (2010)) defined that high phosphate concentrations emerge when the low temperature released. The N:P ratio of 0.328 has been identified which shows the P-limited water condition (Table 2). This may induce the harmful algal bloom because several species (dinoflagellates) have a significant response to P. According to Correll (1998), the high productivity of P leads to a high bacterial population and respiration rates that induce hypoxia and anoxia. The release of P amplifies eutrophication (Zhang *et al*., 2017). This is clear that the high content of P is released together with low-temperature groundwater through seepages. Those conditions also indicate that the unlivable biota in the surrounding seepages is not only affected by the outfall of low-temperature groundwater but also the possibility of blooming tendency. Nevertheless, it needs further study which analyzes nutrient-enhanced algal bloom in the SGD area of North Lombok waters.

Low salinity and relatively high pH influence the concentrations of nutrients in water bodies. According to Scuderi *et al*., (2011), the concentration of nutrients will increase if the salinity is relatively low. While high conductivity shows that the brine (connate) water takes place in the seepages sourced from the combination of saline and fresh waters sink in the sediments.

Table 2. Nutrients and water quality data of SGD sources in the North Lombok Waters

Parameters	**NO_3-N**	**N_{total}**	**PO_4**	**P_{total}**	**Salinity**	**pH**	**Conductivity**
Values	0.24 mg/L	0.18 mg/L	0.54 mg/L	0.55 mg/L	3.03%	8.17	5.05 x 10^4 µS/cm

(Source: Bakti *et al*., 2010)

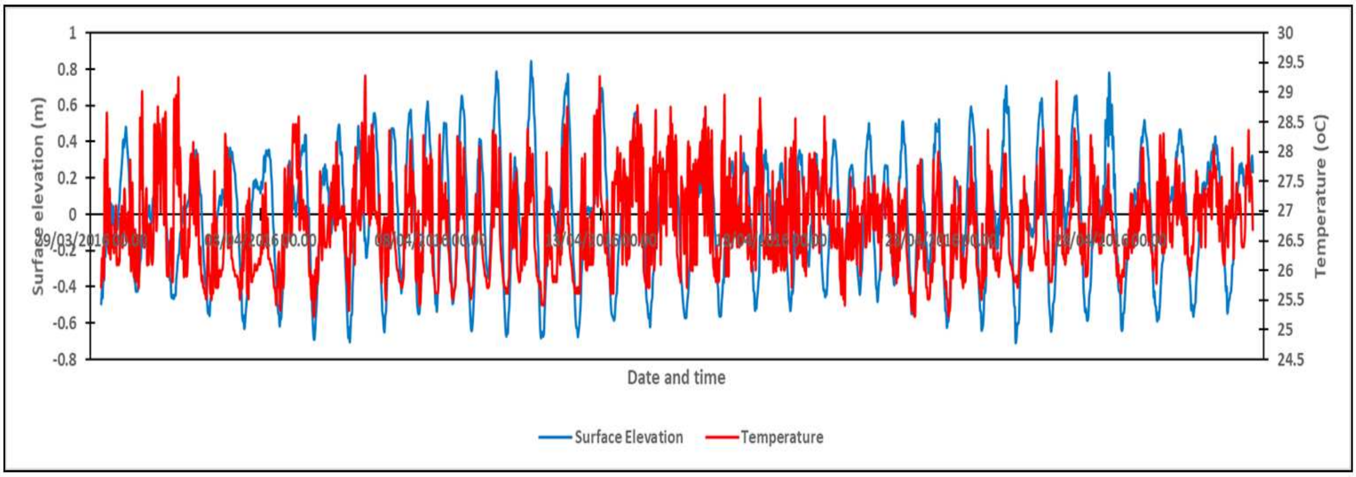


Figure 9. The correlation between tidal elevation changes with temperature fluctuations

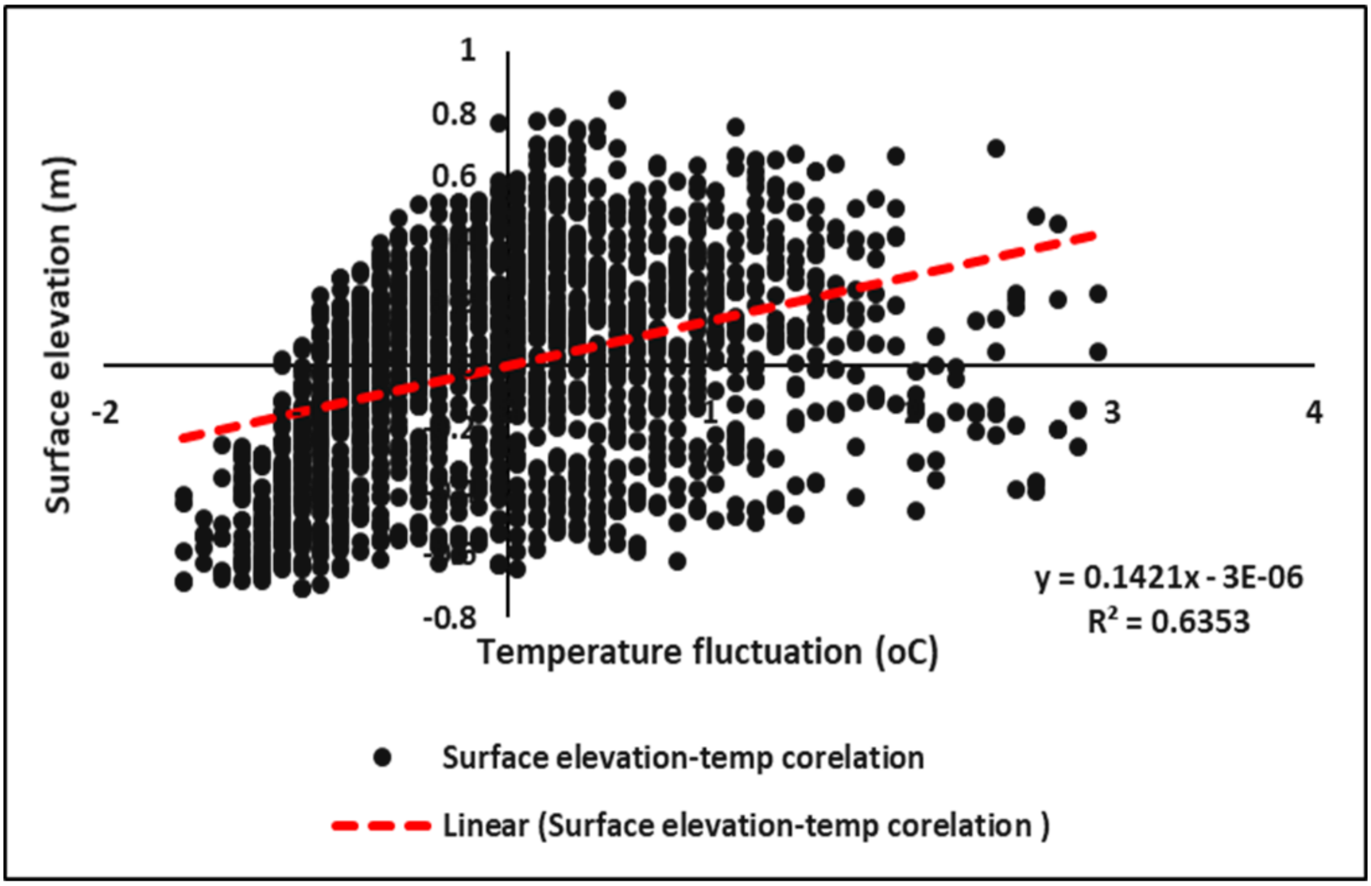


Figure 10. R-square examination between tidal and temperature data

3.4 Tidal-temperature relations in the SGD sources

Sea temperature ranged dramatically from 25.5°C up to 29.5°C while the tidal range reached 1.6 m (Figure 9). The fluctuation of temperature was in conjunction with the surface elevation which reached 29°C and 27.5°C at the spring and the neap tidal conditions respectively. The elevated sea level was followed by temperature fluctuation (tidal pumping regime) (Li *et al*., 2009). The low-temperature of groundwater tremendously predominates the water bodies when the water level decreased.

The largest seepage was located in Karakas Beach which it emerged in the 9-m depth. The shallow water of the SGD area supports the cold groundwater to be well-distributed to the surrounding. The magnitude of submarine groundwater discharge varies seasonally

(Beck *et al.*, 2007). The fluctuation of distributed-groundwater potentially affects the surrounding environment that could hamper the biota survival ability.

To strengthen the result in Figure 9, we assessed the correlation between surface elevation changes and temperature using linear regression. In this case, temperature becomes a dependent variable, while, the surface elevation becomes an independent variable. The R-square value of 0.63, defines that the ability of independent variable (surface elevation) to explain the dependent variable (temperature) was amount 63%. It also indicated that there were 36 percent variances of the dependent variable explained by the other factors. Figure 10 shows that the temperature enhanced around 3^{o}C when the sea level increased and vice versa.

4. Conclusion

Sea current is the main factor triggering the horizontal distribution of groundwater. The water mass transfer is periodically influenced by the wind-wave formation that significantly has impacts the propagation of SGD. The negative velocity of currents indicates that the water mass transport tends to be settled and flowed in the surface bottom which the low-temperature groundwater would be distributed more horizontally. The horizontal distribution of SGD frequently occurs when the flood tides took place, while during ebb tides the distribution is strongly influenced by the rip and longshore currents wherein the propagation of SGD with low temperature is just spinning around the source. The elevated sea level is followed by the temperature fluctuation (tidal pumping regime).

The distribution of temperature in the surrounding may trigger the environment which has a role in controlling the biogeochemical process and the water quality as well. The blooming tendency may occur because the low ratio of N:P has been identified, this may enhance the possibility of toxic algal growth rate (dinoflagellates). The further study focused on nutrient-enhanced eutrophication in the SGD sources of North Lombok waters is necessary to be conducted by which it could reveal the causes of unlivable biota around SGD in the North Lombok waters.

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Authors' Contributions

All authors discussed the results and contributed to from the start to final manuscript; UJW as the main contributor who responsible for developing idea, data analysis, discussing the results and revising this article from the start to final manuscript. While GK as the supporting contributor who designed survey planning and collected in situ data.

Conflict of Interest

The authors declare that they have no competing interests

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